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AXIAL-LOAD FATIGUE TESTS USING LOADING SCHEDULES BASED ON MANEUVER-LOAD STATISTICS

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SUMMARY

Sheet specimens of 7075-T6 aluminum alloy with a theoretical elastic stress concentration factor K_T of 4 were subjected to repeated axial loads. The load amplitudes were held constant or varied by steps to approximate a maneuver-loads spectrum. The variable-amplitude test data were analyzed by assuming linear cumulative damage.

The value of the summation of cycle ratios, $\sum \frac{n}{N}$, was found to vary with "block size," number of load steps, absence of the highest load step, and the addition of loads to simulate negative load factors.

In addition, the effects of adding load steps above the design limit load and of omitting the lowest load step are discussed.

INTRODUCTION

In recent years the fatigue life of aircraft has become increasingly important for safety as well as for economic reasons. In order to evaluate the fatigue characteristics of a new design, the manufacturer has resorted to ad hoc fatigue tests. Such tests require a test program which will satisfactorily represent the complex load history experienced in service. Because it is very time consuming and expensive to represent completely the anticipated service load history, various compromises are usually adopted in the design of the test program. A set of discrete load levels is used to represent the continuous distribution of load peaks encountered in service. Loads which induce stresses below the fatigue limit of the material are often omitted from the load schedule in order to reduce testing time. Loads characteristic of flight at negative load factors are sometimes omitted, and loads associated with the ground-air-ground cycle are handled in a variety of ways. In view of the complications associated with changing the load level during the test, such changes are frequently held to a minimum by breaking the schedule up into blocks considered representative of a tenth, a twentieth, or some other proportion of the anticipated life.

Many questions can be raised as to the interpretation of the results of such tests. The consequences of any particular choice of alternatives is often estimated by application of one of the several cumulative-damage rules and adjustments made to the fatigue life inferred from the test results. The high cost of full-scale fatigue tests, however, has prevented any adequate evaluation of these adjustments. An extensive program has therefore been initiated at the Langley Research Center which, by tests on sheet specimens, attempts to answer some of the questions which arise in the design of a full-scale fatigue test and in the interpretation of the results.

For loading schedules based on the gust-load statistics, some results of this study have been reported in reference 1. The effects on fatigue life estimates of such factors as loading sequence and mean stress were studied for two materials, 2024-T3 and 7075-T6. The present investigation enlarges the scope of the overall program by using maneuver-load statistics to develop a probable load spectrum. Such parameters as the effect of block size and the effect of omitting portions of a typical maneuver-load spectrum are investigated in some detail.

To establish a common denominator for comparison of the fatigue-damage potential of the several different loading schedules studied, values of the summation of the cycle ratio were computed by assuming linear cumulative damage. To reduce the uncertainties in these cumulative-damage calculations, a stress-lifetime relation was established for the specimens used in the variable-amplitude tests. This stress-lifetime relation was established by a series of constant-amplitude tests in which the minimum stress was held constant at a value representative of nominal 1 g stress for fighter aircraft and the values of maximum stress covered the range from level flight to greater than flight limit load factor. Both constant-amplitude and variable-amplitude tests were conducted on notched sheet specimens of 7075-T6 aluminum alloy in axial load.

EXPERIMENTAL PROCEDURES

Fatigue Specimens

The edge-notched specimen configuration (see fig. 1) for these tests had a theoretical elastic stress concentration factor K_T of 4.0. (See ref. 2.) This configuration was chosen because the fatigue behavior closely approximates the fatigue behavior of the best current component design. (See ref. 3.)

The material for this investigation was part of a stock of commercial 0.090-inch-thick 7075-T6 aluminum-alloy sheet retained at the Langley Research Center for fatigue tests. Sheet layouts for this fatigue stock are presented in figure 1 of reference 4 and the material properties are given in table V of reference 5. The tensile properties for this material are given in table I.

Ten specimen blanks were cut from each of several material blanks (12 inches × 35 inches) and identified by adding a number (1 to 10) to the material blank number (ref. 4); thus, a typical specimen number B46N1-4 means the specimen was made of 7075-T6 aluminum alloy (B), taken from the N1 position of sheet 46, and 4 indicates the position within the material blank (B46N1) from which the specimen blank was taken.

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The rolled surfaces of the specimen blank were left as received and the longitudinal edges were machined and notched according to dimensions in figure 1. In order to minimize residual stresses in the notch root due to machining, a small hole was drilled first and enlarged to the proper radius by using progressively larger drills. Drills were used a maximum of 4 times before being resharpened or replaced. A drill press with constant automatic feed was used and drill-size increments were 0.003 inch. The notch was completed by slotting with a 3/32-inch milling tool.

Burrs left in the machining process were removed by holding the specimen lightly against a rotating bakelite dowel impregnated with a fine grinding compound. All specimens were inspected and only those free of surface blemishes in and near the notches were tested.

Testing Machines

The tests were conducted in several axial-load fatigue testing machines (hereafter referred to by a number from 1 to 9) with nominal capacity of ±20,000 pounds. A detailed description of these machines is given in reference 5. The basic machine has a beam excited to vibrate near resonance by a rotating eccentric mass driven at 1,800 cycles per minute by an electric motor. The vibrating beam imparts axial forces to the specimen which acts as one of the supports. Mean loads are applied and maintained by adjusting preload springs.

Machines 6 to 9 were modified to include hydraulic loading at approximately 20 cycles per minute (fig. 2) so that small numbers of high loads could be applied accurately. This modification is described in some detail in reference 1. Essentially the modification included an electrically driven hydraulic pump, 4-way valve, hydraulic cylinder, semiautomatic controls, and a recorder for monitoring the loads.

The load-measuring apparatus was calibrated periodically. The error in the load-measuring apparatus was estimated not to exceed ±12.5 pounds. The load on the specimen was maintained within ±50 pounds of the desired load for hydraulic loading and within ±12.5 pounds for subresonant loading.

Test Procedure

Constant-amplitude tests.- Specimens which were expected to fail (separate into two pieces) in more than 10,000 cycles were tested at 1,800 cycles per minute using the procedure described in reference 5. For expected lives of less than 10,000 cycles, the specimens were tested in the hydraulic machines (6 to 9). The procedure was the same as that used in reference 1 except that the minimum load was applied and maintained by the preload springs and the specimen was cycled between this load and the maximum.

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Variable-amplitude tests.- All the variable-amplitude tests were conducted in the modified machines (6 to 9) by using only hydraulic loading. The same procedure as that of reference 1 was used with the exception that the minimum load instead of the mean load was applied with the preload springs. In general, similar tests were conducted concurrently.

Loading Schedules

The load schedules for the present investigation were based on the frequency of occurrence of peak loads in maneuvering flight. Maneuver-load statistics for the frequency of positive load factor peaks (ref. 6) and for negative load factor peaks (ref. 7) were transformed into a spectrum of peak stress against cumulative frequency. For this transformation the total peak count was arbitrarily selected as 10,000. Also a design load factor of 7.3 and a 1 g (level flight) stress equal to 7 ksi were assumed. The maneuver load statistics for the stress frequency spectrum are presented in table II.

In order to select discrete load levels to represent this continuous spectrum, linear cumulative damage being assumed, it is necessary to have an S-N curve for the same specimen configuration and loading conditions. Therefore constant-amplitude fatigue tests were conducted for which the specimen was cycled between a constant minimum stress (7 ksi) and various maximum stresses. A graphical presentation of the constant-amplitude fatigue-test results is given in figure 3. The constant-amplitude fatigue-test results will be discussed in more detail in later sections.

Each of the discrete load levels used in these tests was chosen by a numerical integration of theoretical damage to produce the same linear damage increment in the same number of cycles as occur in a corresponding band of the stress frequency spectrum. A somewhat detailed explanation of the numerical integration of the damage is presented in reference 1. The results of the integration are presented in table III. In table III the stress band limits, the stress level representing each stress band, the number of cycles each load level is applied, and the cycle ratio n/N (where n is the number of cycles applied and N is the fatigue life at the same stress level) for each load level are presented.

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The number of cycles were adjusted so that the sum of the cycle ratios $\sum \frac{n}{N}$ was approximately 0.1. This then established the block size and, linear cumulative damage being assumed, failure would be expected at the completion of the tenth block.

The numerical integration process was used to develop the "standard" load schedule (No. 1) which represented positive load factors from 1 g to design limit load. This range was assumed to be reasonable because loads above design limit are not usually considered in design and negative loads occur very infrequently and are small enough to be considered inconsequential. This standard schedule was operated on in several ways to determine whether various effects were present. Other schedules were developed to include positive load factors above design limit load or negative load factors. The last load schedule was designed to cover the full range of the loads investigated, negative loads being paired with and immediately following positive loads which occurred with equal frequency, and made use of data obtained in foregoing tests in this investigation. A description of each load schedule follows:

Load schedule 1.- This eight-step load schedule is limited to part of the spectrum, that is, positive load factors between 7 ksi (1 g) and design limit load. (See table III and fig. 4(a).) This standard load schedule was varied in three ways. First the number of cycles at each load level was multiplied by a constant (0.1, 0.3, or 5.0) to provide schedules with various block sizes to evaluate possible block size effects. (See ref. 1.) The second variation was to truncate the schedule at either the high stress end (minus load step 8) or the low stress end (minus load step 1). Load step 8 was omitted to determine the effect of this load level on the fatigue life. Occasionally, it becomes necessary to placard on operational aircraft; thus the magnitude of the loads to be encountered is lowered. Although this would change the whole spectrum of loads, only the highest load level was altered in this investigation. Load step 1 was omitted to determine whether loads below the fatigue limit, for which $n/N = 0$ since $N \rightarrow \alpha$, have an effect on fatigue life.

This is of great interest to the test designer because the lowest step usually contains at least 30 percent of the cycles in one block and therefore consumes a large part of the testing time. The third variation was to represent the same portion of the spectrum (1 g minimum to design limit load) with four load steps. (See table III and fig. 4(b).) This was accomplished by combining two load steps into one load step having a different stress level, numerical integration for this change was performed in stress bands twice the size of those for the standard schedule. This change was made to determine whether the number of stress levels used to approximate the stress spectrum would have an effect on the fatigue life. (See also ref. 1.)

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Load schedule 2.- To obtain this schedule two load levels, representing positive load factor peaks above design limit load, were added to the standard load schedule. (See table III and fig. 4(c).) This schedule then represents the full positive load spectrum in figure 3. The effect of loads above design limit is important because it is known that design limit load is exceeded with appreciable frequency in operational vehicles.

Load schedule 3.- Two load levels were added to the standard load schedule to evaluate the effect of loads representing negative load factor peaks on fatigue life. (See table III and fig. 4(d).) Many investigators omit these negative loads because they are relatively small in magnitude and occur very infrequently. However, since they do occur with a known frequency, their influence on fatigue life should be known. In this schedule the negative loads were applied as discrete load steps which theoretically caused no damage, $n/N = 0$.

Load schedule 4.- This load schedule was designed to represent the complete range of maneuvering statistics as presented in table II. The results of tests previously conducted were utilized to shorten the testing time and to make the loading schedule realistic. Load level 1 of the standard load schedule was found not to contribute a significant amount of damage (to be discussed in detail in a later section) and was therefore not used in this load schedule. (See table III.) In order to represent the negative load peaks and the load peaks above design limit load with as few load steps as possible, the negative cycles were combined with positive cycles so that one negative cycle followed one positive cycle. In order to make the number of positive and negative load cycles approximately equal, load step 8 and load step 10 (load schedule 2) were combined with load steps 1(a) and 1(b) (load schedule 3), respectively. (See table III and fig. 4(e).)

For tests using this load schedule, the cycle ratio for the combined cycles had to be determined by using an S-N curve for which the loading conditions were the same, that is, same minimum and maximum stresses.

This curve was not available. Therefore, the value of N for the combined stress cycles was interpolated from the S-N curves presented in reference 1. Because the stress range was greater, although the maximum stress was the same, the cycle ratio was much higher for the combined stress cycles than for either the positive load cycles or the negative load cycles, or the sum of these two ratios. Since it is assumed that loading-sequence effects found in reference 1 would also be present in this investigation, it was decided to use a randomized sequence of loading. Therefore, in all the tests the load steps within each block were applied in a random manner, by using a sequence obtained from a table of random numbers. Each block had a different random schedule until the twentieth block; thereafter the schedule for the first 20 blocks was repeated.

RESULTS

Test Data

<u>Constant-amplitude tests</u>.- The results of the constant-amplitude fatigue tests are given in table IV and are shown plotted in figure 3. In figure 3 the symbols represent the geometric means of the fatigue lives at a given stress level, the ticks represent the scatter limits for the data, and the number corresponds to the number of data points represented by the geometric mean. The solid curve represents the S-N curve faired through the data.

<u>Variable-amplitude tests</u>.- The results of the variable-amplitude fatigue tests are presented in table V. The table is divided into sections corresponding to the various test groups. Included in the tables are the number of the machine in which the specimen was tested, the block and load step at failure, and the specimen life (total cycles).

Analysis of Data

Because of its simplicity and general usage, the linear cumulative damage index $\sum \frac{n}{N}$ was selected as the means for comparing the results of various test groups. Therefore, each variable-amplitude test result was reduced to a value of $\sum \frac{n}{N}$.

The Proschan method[1] was used to eliminate any test in which the life was widely displaced from the lives of other tests in that group.

[1]Unpublished paper: "How to Decide Objectively Whether an Outlying Observation Should be Rejected," by Frank Proschan, 1952.

This method eliminated only four tests of 64. These four tests are identified in table V by a footnote.

The values of $\sum \frac{n}{N}$ for the variable-amplitude tests are given in table V. In addition, the values of $\sum \frac{n}{N}$ are presented graphically in figure 5. In figure 5 the ticks represent the limits of scatter in the test data, the symbols represent the geometric mean of the group of data, and the number corresponds to the number of tests in that group.

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In order to establish more definitely whether a given change in test schedule produced an effect on fatigue life, the geometric means of $\sum \frac{n}{N}$ for groups of test data were compared statistically by using reference 8 as a guide.[2] The distributions of $\sum \frac{n}{N}$ were assumed to be log normal and a 95-percent confidence level was used. The standard deviations of the logarithms of $\sum \frac{n}{N}$ were compared by the "F" test (that is, sample standard deviations are (or are not) significantly different) and the means of the logarithms of $\sum \frac{n}{N}$ were compared by the "t" test (that is, sample means are (or are not) significantly different).

The results of the "t" tests and the ratio of the $\sum \frac{n}{N}$ geometric means for each of the test groups compared are presented in table VI.

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[2]On page 44 of reference 8, $\beta = 1 - \frac{\alpha}{2}$ instead of $\beta = 1 - \alpha$; therefore, in tables V and VIII of reference 8 values of $t_{0.975}$ and $F_{0.975}$, respectively, were used for the statistical analysis. β is the significance level and α is the preassigned significance level or chosen risk.

DISCUSSION OF RESULTS

General

The scatter in the constant-amplitude tests is not considered excessive (ticks in fig. 3). It should be noted that this S-N curve is for constant minimum stress rather than for the more conventional constant mean stress. The scatter in the value of $\sum \frac{n}{N}$ for a group of variable-amplitude tests (ticks in fig. 5) is generally less than in the constant-amplitude tests and does not exceed 1.7 to 1 for any group of tests. Results of all the tests yielded values of $\sum \frac{n}{N}$ greater than 1.0, a trend that is consistent with other tests for which the mean stress was greater than 0. This trend has been noted by many investigators. Differences between individual sets of data require more detailed study. Although the ratio of the geometric means of $\sum \frac{n}{N}$ for any comparison of test groups is less than 2 to 1, several trends are noticeable. Because these trends are not predictable, linear cumulative damage being assumed, it would seem that actual damage accumulation is affected by the systematic changes in the loading history.

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Variable-amplitude fatigue life has many conflicting or interacting facets, many of which are not completely understood. Perhaps the most important ones are residual stresses, crack initiation, crack propagation, and residual static strength. It is difficult to explain fatigue-crack propagation characteristics under varied loading conditions without the aid of the concept of residual stresses. If it is recognized that variable-amplitude fatigue life is divided into crack initiation and crack propagation phases, then it is equally difficult to explain variations in life without considering residual stresses.

For the purpose of this discussion the following point of view is adopted. Residual stresses are present in all of the tests and have strong influence on crack initiation and propagation. There is a finite time required to initiate the crack (fatigue-crack initiation phase) followed by crack propagation (fatigue-crack propagation phase). Failure is defined as the parting of the specimen into two parts.

It is not the intent of this paper to present all the concepts found in the literature on the subjects of crack propagation, residual stresses, and residual static strength. The following discussions are intended to show only that the differences or absence of differences in fatigue damage under varied load history can be reasonably explained on the basis of the premises established.

Residual Stresses

Production of residual stresses.- It is well known that fatigue life (constant or variable amplitude) can be improved by introducing beneficial residual stresses in the specimen. (See ref. 9.) One method for obtaining beneficial residual stresses is to load the specimen until plastic deformation occurs at the root of a stress raiser (notch, hole, crack, etc.). When the specimen is unloaded, the plastically deformed material in the root of the stress raiser cannot assume its original length and is therefore subjected to compressive stress. The magnitude of this compressive stress increases with the magnitude of the applied load. Although the exact values of the residual stresses during fatigue cycling are not known, some investigators have found values of residual stresses approaching the yield strength in axial-load tests with notched specimens.

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Fatigue-crack initiation phase.- The effect of residual stresses has been used by many investigators to improve fatigue life by applying a high load (prestress) prior to or early in the fatigue test. This high load is generally applied from the mean stress to maximum value and back to the mean stress (half-cycle). The increase in fatigue life due to prestressing has been attributed to a delay in the initiation of a fatigue crack. The delay is dependent on the difference in the magnitudes of the prestress load and the cyclic stress, that is, the larger the difference, the longer the delay. Because the delay in crack initiation is, in general, a finite number of cycles, it is assumed that the beneficial effects of the prestress decay as cyclic loads are applied. Therefore, the benefits of the residual stress are lost when a crack begins to propagate.

The application of a high load periodically during the fatigue life would then appear to be another method of increasing fatigue life. Heywood (ref. 10) conducted tests in which the high load was applied (1) as a single preload, (2) as a multiple preload, and (3) periodically during the test. The test results strongly support the concept of increased benefits from periodically applied high loads.

It seems reasonable, from the foregoing discussion, that load schedules which had different maximum loads applied periodically would have different lives for the crack initiation phase.

Fatigue-crack propagation phase.- Considerable time and emphasis have been placed on the problem of fatigue-crack propagation. The basic mechanism is still cloudy and there is no way to predict crack propagation under variable loading. References 11 and 12 present data on the delay in crack propagation due to changes in stress level after a crack had begun to propagate. The delays observed when the stress level changes from a high to a low value have been explained on the basis of residual stresses which develop at the tip of the crack. As would be expected, the delay in crack propagation increases as the difference between stress levels increases. As in the case of crack initiation the effect of the residual stresses decays as the specimen is cycled and slowly the crack begins to propagate again.

In the case of multilevel fatigue tests, different test results can be obtained by varying the order in which the loads are applied. (See ref. 1.) When the load steps are applied in a random order, damage due to each load level becomes unpredictable unless it is known how much each cycle of each load level contributes to the decay of the residual stresses or to the propagation of a crack. Until such information is available, only qualitative methods can be used to predict variable-amplitude fatigue life.

Residual Static Strength and Failure

Failure of the specimen occurs when the applied load equals the residual static strength of the specimen. It is well known (see ref. 13) that the residual static strength of a specimen first decreases very rapidly as a crack is initiated and then deteriorates further with increasing crack length. Residual stresses seem to have very little, if any, effect on the residual static strength. Thus, it seems that high loads, which produce residual stresses to increase fatigue life by retarding crack initiation and propagation, may also shorten fatigue life by exceeding the residual static strength of a specimen, which contains a short fatigue crack.

From the preceding discussions of residual stresses, crack initiation and propagation, and residual static strength, it would seem obvious that each must be considered when trying to predict or explain variations in variable-amplitude fatigue life. Therefore, the following sets of data are discussed with this end in view.

Effect of Block Size

Four block sizes with approximately 300 to 15,000 cycles per block were used. (See load schedule No. 1, table III.) As can be seen in figure 5 the value of $\sum \frac{n}{N}$ increased with block size and then decreased. The statistical analysis indicated a significant difference in the geometric means of $\sum \frac{n}{N}$ in three of the six comparisons. (See table VI.)

Beneficial residual stresses were present in these tests, as evidenced by the fact that $\sum \frac{n}{N} > 1$, but the exact reason for variation in life with block size cannot be explained at this time. Possible lines of investigation which might explain this variation are systematic study of (1) fatigue crack propagation in multilevel tests, and (2) the relative effect of single or multiple cycles at the high-load level.

Effect of Truncating the Load Schedule

The lowest stress level in load schedule 1 was well below the fatigue limit and theoretically contributed no damage ($n/N = 0$, since $N \rightarrow \alpha$) although this stress level contributes approximately one-third of the total cycles. A comparison of results for tests with and without this load level (fig. 5) shows a slight increase in $\sum \frac{n}{N}$ which was not found to be significant (table VI). The small increase in life might be explained by the actual damage contributed by the lowest load level after the fatigue crack had begun to propagate; thus, the effective fatigue limit is lowered. Another possible explanation is that this omitted load level probably contributes to the decay of the residual compressive stresses caused by higher loads.

Omitting the highest load level in load schedule 1 gave a statistically significant decrease in $\sum \frac{n}{N}$ (table VI) when compared with tests with the highest load level included (table III and fig. 5). This decrease is probably due to the decrease in magnitude of the residual stresses; thus, the crack initiation and propagation phases of the test are shortened. Although the critical crack length for residual static strength at the highest load was increased, the increase in the crack initiation and propagation rates overshadows this effect.

Effect of Reducing the Number of Load Steps

In the series of tests for which the number of load steps was reduced from 8 to 4 (table III) the reduction in the geometric mean of

$\sum \frac{n}{N}$ was significant (table VI and fig. 5). This reduction is probably due to (1) a decreased magnitude of beneficial residual stresses because the highest load had been reduced, (2) a possible accumulation of actual damage from the lowest load level after the crack had been initiated, since the lowest load is now closer to the fatigue limit S_e, and (3) an increase in actual damage at the highest load because of the increased number of applications.

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In reference 1 there was not a significant difference found between 8 and 18 stress levels for gust-load histories. In the light of the present results it might be surmised that there is a minimum number of stress levels above which the number of stress levels used would have no effect.

Effect of Adding Load Levels Above Design Limit Load

For tests in which two load levels above design limit load were added (load schedule 2), $\sum \frac{n}{N}$ decreased slightly but not significantly when compared with results of tests without these load levels (table VI). The predominant effect of the higher loads appears to have been to cause static failure when a shorter crack was present. Since the critical crack length was shorter for residual static strength considerations, but the difference in life was small, it would seem that the higher loads did increase the residual stress effect.

Effect of Including Negative Load Factors

Two methods of including the negative load factors were used, in one method the negative loads were applied in groups (load schedule 3). The other method combined the negative and positive cycles such that each negative cycle followed a positive cycle (load schedule 4).

For the tests in which negative load steps were applied in groups, a statistically significant reduction in $\sum \frac{n}{N}$ (table VI) was present when compared with similar tests without negative loads (table V and fig. 5). This reduction in $\sum \frac{n}{N}$ is thought to be caused by the reduction of beneficial residual stresses when compression loads were applied, thus crack initiation and propagation rates are increased.

The amount the residual stresses are lowered appears to be dependent on the magnitude of the compressive load. The relative location of the highest load and the negative loads within the randomized blocks is also important because (1) damage from those loads applied between the highest load and the negative load will be reduced by the residual compressive stress, and (2) damage from those loads following the negative loads may be greater than that computed because the residual stresses may be tensile.

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The values of $\sum \frac{n}{N}$ for tests with combined cycles were found to be significantly lower than those for tests without negative loads but not significantly different (table VI) from tests with loads applied in groups. The reduction in $\sum \frac{n}{N}$ is thought to be caused by a reduction in or elimination of the beneficial residual stresses when compressive loads are applied. This load schedule had a positive high load followed by a negative load and formed one load cycle. In this case the compressive one-half cycle decreased the effect of the residual stresses due to the tensile one-half cycle. The exact value of the residual stress is not known and it is possible that a tensile residual stress existed in the specimen following the full cycle. This action was deleterious to the fatigue life until a load was applied which was sufficient in magnitude to reverse the nature of the residual stress. The cycle which produced the maximum compressive residual stress was lower than the maximum load and therefore the increase in life was less than that assumed from similar tests without negative loads. A second reason for the decrease in $\sum \frac{n}{N}$ for tests with combined cycles is the reduced crack length for which the specimen residual static strength becomes critical.

Another factor which may have had a small effect on the value of $\sum \frac{n}{N}$ is the reliability of the assumed N values in $\sum \frac{n}{N}$ for the combined load steps. As has been stated earlier, these values were interpolated and some error is probable.

Other Observations

Load step at failure.- In 58 of the 64 tests the specimen failed during the application of the highest load. This failure then illustrates the importance of residual static-strength considerations. For, although a high load applied periodically does influence the fatigue life by introducing beneficial residual stresses, there is also the possibility that the load will exceed the residual static strength of the specimen containing a fatigue crack. The higher this load the shorter the fatigue crack need be for failure conditions to be satisfied.

Fracture surface.- In all tests the specimen fracture surface bore typical variable-amplitude fatigue markings, that is, dark, coarse bands alternating with smooth shiny bands. The dark bands are thought to be caused by semibrittle crack propagation during the application of one or more high loads and the shiny, smooth bands by the application of many small loads.

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Method of comparison.- As has been previously stated, linear cumulative damage has been assumed in the analysis of these tests because of its simplicity. However, airline operators are interested in flying time, not theoretical damage; therefore, many fatigue tests are designed so that a block represents a given number of flights or flight hours. If the test results of this investigation had been compared by this method it would be possible to obtain different results. For example, load schedule 3 produced the lowest value of $\sum \frac{n}{N}$ while load schedule 4 produced the shortest life if number of blocks to failure was the criterion. (See table V.) This latter comparison more forcefully demonstrates the deleterious effect of removing residual stresses as soon as they are formed and of the tendency for high loads to cause complete failure when short cracks are present.

CONCLUSIONS

The data obtained from axial-load fatigue tests of 7075-T6 aluminum-alloy sheet specimens, programed to simulate manuever-load experience, support the following conclusions:

1. All values of the summation of cycle ratios $\sum \frac{n}{N}$ at failure were greater than 1 which is due to the formation of beneficial residual stresses during application of the highest load. (In the ratio n/N, n is the number of cycles applied and N is the fatigue life at the same stress level.)

2. A standard load schedule, consisting of 8 load levels and representing positive load peaks from the 1 g level-flight stress to

design limit load, was varied or modified in several ways. The following effects were present when compared with this standard load schedule.

(a) Adding load levels to simulate negative load factors gave a significant reduction in $\sum \frac{n}{N}$. Adding load levels to simulate loads above design limit did not give a significant change in $\sum \frac{n}{N}$.

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(b) Truncating the load schedule at the high stress end decreased the value of $\sum \frac{n}{N}$ significantly, whereas truncating the load schedule at the low stress end did not have a significant effect on $\sum \frac{n}{N}$.

(c) $\sum \frac{n}{N}$ increased and then decreased with increasing block size.

(d) The value of $\sum \frac{n}{N}$ was greater when using eight steps to approximate the load spectrum than when using four steps to simulate the same load experience.

Most of the variations in fatigue life observed in this investigation may be explained qualitatively with the aid of residual stresses and residual static strength considerations.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., February 13, 1962.

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TABLE I

TENSILE PROPERTIES OF ALUMINUM-ALLOY MATERIAL TESTED

[7075-T6 (152 tests); data from ref. 5]

	Average	Minimum	Maximum
Yield stress (0.2-percent offset), ksi	75.50	71.54	79.79
Ultimate tensile strength, ksi	82.94	79.84	84.54
Total elongation (2-inch gage length), percent	12.3	7.0	15.0

TABLE II

MANEUVER-LOAD STATISTICS

Acceleration, g	Equivalent stress, ksi	Number exceeding
Positive load distribution		
1	7.0	10,000
2	14.0	5,600
3	21.0	2,800
4	28.0	1,220
5	35.0	430
6	42.0	115
7	49.0	23
7.3	51.1	13
8	56.0	3.7
9	63.0	0.53
Negative load distribution		
0	0	140
-1	-7.0	12
-2	-14.0	1.3

TABLE III

LOADING SCHEDULES FOR VARIABLE-AMPLITUDE FATIGUE TESTS SIMULATING A MANEUVER-LOAD SPECTRUM

Step	Stress range, ksi	Representative stress, ksi	n/step	n/N Step	Step	Stress range, ksi	Representative stress, ksi	n/step	n/N Step
Load schedule 1 (8 steps)					Load schedule 2				
[b]1	7.0-12.5	9.8	[a]1,030	[a]0.000000	1	7.0-12.5	9.8	1,030	0.000000
2	12.5-18.0	15.3	[a]780	[a].000050	2	12.5-18.0	15.3	780	.000050
3	18.0-23.5	20.8	[a]510	[a].006806	3	18.0-23.5	20.8	510	.006806
4	23.5-29.0	26.2	[a]300	[a].018745	4	23.5-29.0	26.2	300	.018745
5	29.0-34.5	31.7	[a]180	[a].025297	5	29.0-34.5	31.7	180	.025297
6	34.5-40.0	37.0	[a]88	[a].023588	6	34.5-40.0	37.0	88	.023588
7	40.0-45.5	42.3	[a]35	[a].016417	7	40.0-45.5	42.3	35	.016417
[b]8	45.5-51.1	48.8	[a]11.5	[a].009070	8	45.5-51.1	48.8	11.5	.009070
					[c]9	51.1-56.5	53.4	3.2	.003899
			$\sum$ 2,935	[a]0.099973	[c]10	56.5-62.0	58.6	.7	.001450
								$\sum$ 2,939	0.105322
Load schedule 1 (4 step)					Load schedule 3				
1	7.0-18.0	12.5	1,810	0.000050	[d]1(b)	-14.0--7.0	-9.8	1.5	0.000000
2	18.0-29.0	23.0	810	.024000	[d]1(a)	-7.0- .0	-2.8	15	.000000
3	29.0-40.0	33.5	268	.047017	1	7.0-12.5	9.8	1,030	.000000
4	40.0-51.1	44.0	46.5	.024538	2	12.5-18.0	15.3	780	.000050
					3	18.0-23.5	20.8	510	.006806
			$\sum$ 2,935	0.095605	4	23.5-29.0	26.2	300	.018745
					5	29.0-34.5	31.7	180	.025297
					6	34.5-40.0	37.0	88	.023588
					7	40.0-45.5	42.3	35	.016417
					8	45.5-51.1	48.8	11.5	.009070
								$\sum$ 2,952	0.099973

[a]This schedule was modified by multiplying by 0.1, 0.3, and 5 to study block size effect.

[b]For two series of tests either the highest (8) or the lowest (1) load step was omitted.

[c]Steps 9 and 10 represent loads above design limit load added to schedule 1.

[d]Steps 1(a) and 1(b) represent negative load factors added to schedule 1.

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TABLE III - Concluded

LOADING SCHEDULES FOR VARIABLE-AMPLITUDE FATIGUE TESTS

SIMULATING A MANEUVER-LOAD SPECTRUM

Step	Stress range, ksi	Representative stress, ksi	n/step	$\frac{n/N}{\text{Step}}$
Load schedule[e] 4				
2	12.5-18.0	15.3	780	0.000050
3	18.0-23.5	20.8	510	.006806
4	23.5-29.0	26.2	300	.018745
5	29.0-34.5	31.7	180	.025297
6	34.5-40.0	37.0	88	.023588
7	40.0-45.5	42.3	35	.016417
8(a)	-7.0-51.1	-2.8 48.8	11.5	[f].032857
10(b)	-14.0-62.0	-9.8 58.6	1.5	[f].015000
			$\sum$ 1,906	0.138860

[e]This is a combination of schedules 1, 2, and 3.

[f]The value of N in n/N for steps 8(a) and 10(b) are interpolated from S-N curves in reference 1.

TABLE IV

RESULTS OF CONSTANT-AMPLITUDE AXIAL-LOAD FATIGUE TESTS OF 7075-T6 ALUMINUM-ALLOY

SHEET SPECIMENS WITH S_{min} = 7 ksi and K_T = 4.0, EDGE NOTCH

Specimen	Machine	Life, cycles
S_{max} = 65 ksi		
B50N1-6	8	309
B52N1-6	8	305
B93N1-7	7	283
B92N1-9	6	275
B128S1-3	9	246
Geometric mean		282
S_{max} = 61 ksi		
B92N1-10	9	441
S_{max} = 60 ksi		
B128S1-5	8	521
B128S1-8	8	476
B128S1-6	9	442
B92N1-8	7	436
B93N1-2	6	387
Geometric mean		450
S_{max} = 55 ksi		
B128S1-7	8	748
B93N1-6	9	744
B129S1-2	8	673
B93N1-8	7	618
B93N1-9	6	573
Geometric mean		667
S_{max} = 50 ksi		
B130S1-6	8	1,186
B93N1-4	6	1,119
B93N1-5	9	1,019
B54N1-2	9	1,000
B126S1-10	9	913
B93N1-3	7	834
B126S1-5	9	610
Geometric mean		935
S_{max} = 45 ksi		
B93N1-10	7	1,739
B93N1-1	9	1,671
B92N1-5	6	1,659
B95N1-3	6	1,425
B59N1-10	6	1,237
Geometric mean		1,534
S_{max} = 40 ksi		
B130S1-8	8	3,726
B127S1-3	8	3,352
B126S1-6	9	2,991
B53N1-1	7	2,945
B53N1-9	7	2,864
B126S1-4	9	2,795
B51N1-7	8	2,653
B127S1-10	9	2,615
Geometric mean		2,938
S_{max} = 35 ksi		
B49N1-4	6	5,305
B53N1-3	7	5,238
B53N1-2	9	4,737
B49N1-1	8	4,300
B54N1-10	9	2,892
Geometric mean		4,393
S_{max} = 30 ksi		
B54N1-3	6	10,150
B54N1-9	6	10,070
B87N1-5	6	9,720
B86N1-2	6	8,870
B87N1-3	6	8,390
Geometric mean		9,413
S_{max} = 25 ksi		
B87N1-6	6	22,740
B86N1-5	6	20,590
B86N1-8	6	19,610
B86N1-3	6	19,150
B86N1-9	6	18,420
Geometric mean		20,040
S_{max} = 23 ksi		
B53N1-8	2	39,000
B51N1-1	2	35,000
B53N1-6	7	34,000
B51N1-4	2	32,000
B53N1-5	2	22,000
Geometric mean		31,830
S_{max} = 21 ksi		
B54N1-6	1	182,000
B126S1-1	8	75,690
B49N1-5	6	69,620
B54N1-1	9	62,370
B49N1-3	9	54,040
B86N1-4	7	41,940
Geometric mean		74,470
S_{max} = 19 ksi		
B51N1-3	5	718,000
B86N1-10	9	549,240
B86N1-1	1	115,000
B87N1-9	6	85,030
B87N1-7	7	56,590
Geometric mean		185,200
S_{max} = 18 ksi		
B53N1-7	2	20,805,000
B87N1-2	6	8,510,000
B86N1-7	7	2,647,420
B87N1-4	6	388,820
Geometric mean		4,520,000
S_{max} = 17 ksi		
B87N1-10	5	95,811,110
B130S1-10	5	64,297,610
B127S1-9	8	40,019,300
B87N1-1	5	19,523,000
Geometric mean		58,480,000
S_{max} = 13 ksi		
B130S1-4	8	>101,502.890
B130S1-3	6	>81,000,000
B130S1-2	9	>20,521,610
Geometric mean		

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TABLE V

RESULTS OF VARIABLE-AMPLITUDE AXIAL-LOAD FATIGUE TESTS OF 7075-T6 ALUMINUM-ALLOY SPECIMENS USING A MANEUVER-LOAD SPECTRUM WITH S_{min} = 7 ksi and K_T = 4.0, EDGE NOTCH

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Load schedule 1 (× 0.1); 293 cycles/block					
B94N1-6	9	172	8	50,301	1.72
B56N1-7	8	167	8	48,957	1.66
B50N1-4	6	159	8	46,500	1.59
B128S1-10	6	124	8	36,340	1.23
B50N1-8	7	112	8	32,679	1.12
B52N1-7	7	105	8	30,757	1.05
Geometric mean				40,150	1.37
Load schedule 1 (× 0.3); 879 cycles/block					
B95N1-6	8	80	1	69,515	2.37
B90N1-3	9	72	8	62,808	2.16
B92N1-7	7	69	8	59,932	2.05
B94N1-7	9	68	8	59,778	2.03
B95N1-9	6	61	8	53,129	1.81
B95N1-5	8	50	8	43,119	1.47
Geometric mean				57,420	1.96
Load schedule 1 (8 step); 2,934 cycles/block					
B52N1-4	8	24	8	69,911	2.34
B95N1-2	7	23	8	64,694	2.23
B51N1-2	6	21	8	59,815	2.04
B50N1-9	8	20	8	55,766	1.91
B56N1-1	6	19	8	54,083	1.85
B50N1-5	6	19	8	54,082	1.85
B52N1-2*	6	13	8	35,250	1.22
Geometric mean				59,440	2.02
Load schedule 1 (× 5.0); 14,670 cycles/block					
B52N1-9	8	5	8	70,369	2.04
B94N1-10	8	5	8	70,350	2.02
B92N1-4	7	4	7	56,324	1.76
B52N1-5	7	4	7	56,313	1.75
B94N1-1	9	4	7	56,257	1.73
B52N1-8	6	4	8	56,133	1.67
Geometric mean				60,610	1.82
Load schedule 1; load step 1 omitted					
B91N1-8	7	24	8	45,186	2.34
B129S1-1	7	24	8	45,182	2.34
B91N1-7	8	22	8	40,032	2.12
B128S1-2	8	22	8	40,031	2.12
B52N1-10	8	22	8	40,031	2.12
B91N1-3	7	21	8	39,110	1.96
B51N1-9*	9	11	8	19,649	1.09
Geometric mean				41,520	2.16

*Not included in geometric mean.

TABLE V - Concluded

RESULTS OF VARIABLE-AMPLITUDE AXIAL-LOAD FATIGUE TESTS OF 7075-T6 ALUMINUM-ALLOY SPECIMENS USING A MANEUVER-LOAD SPECTRUM WITH S_{min} = 7 ksi and K_T = 4.0, EDGE NOTCH

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Load schedule 1; load step 8 omitted					
B51N1-8	8	22	7	61,399	1.92
B92N1-6	8	21	7	59,252	1.82
B56N1-10	7	21	7	59,249	1.82
B128S1-9	9	21	7	59,248	1.82
B56N1-2	6	19	7	53,966	1.71
B52N1-3	6	18	7	52,257	1.60
B51N1-5*	6	13	7	35,094	1.10
Geometric mean				57,470	1.78
Load schedule 1 (4 step)					
B97N1-3	8	19	4	54,819	1.78
B97N1-5	7	18	4	52,727	1.72
B96N1-9	8	18	4	52,699	1.70
B96N1-4	8	18	4	52,687	1.70
B96N1-2	7	17	4	46,894	1.54
B97N1-2	9	15	4	43,889	1.41
Geometric mean				50,470	1.64
Load schedule 2					
B94N1-5*	8	27	10	79,069	2.80
B90N1-2	8	21	10	60,586	2.19
B96N1-1	6	21	10	60,586	2.19
B90N1-1	8	19	10	54,797	2.00
B90N1-5	7	16	10	46,978	1.67
B91N1-6	9	16	10	46,978	1.67
B94N1-2	8	16	10	46,977	1.67
Geometric mean				52,470	1.88
Load schedule 3					
B97N1-4	9	14	8	40,457	1.35
B104N1-2	9	13	8	35,705	1.26
B104N1-10	6	13	8	35,696	1.25
B96N1-3	7	12	8	32,466	1.10
B104N1-6	7	12	8	32,462	1.10
B97N1-7	7	11	7	29,511	1.01
Geometric mean				34,210	1.17
Load schedule 4					
B109N1-7	9	11	10(b)	20,155	1.50
B109N1-5	6	11	10(b)	20,155	1.50
B104N1-8	9	11	8(a)	19,067	1.40
B109N1-10	7	10	10(b)	17,154	1.26
B109N1-8	6	9	10(b)	15,429	1.15
B104N1-1	7	8	10(b)	15,159	1.09
Geometric mean				17,730	1.31

*Not included in geometric mean.

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TABLE VI

RESULTS OF STATISTICAL ANALYSIS OF VARIABLE-AMPLITUDE FATIGUE TESTS

Side group \ Top group	Schedule 1 (× 0.1)	Schedule 1 (× 0.3)	Schedule 1	Schedule 1 (× 5)	Schedule 1	Schedule 1 Minus load 1	Schedule 1 Minus load 8	Schedule 1 (8 step)	Schedule 1 (4 step)	Schedule 1	Schedule 2	Schedule 3	Schedule 4
Schedule 1 (× 0.1)		Yes	Yes	Yes									
Schedule 1 (× 0.3)	0.70		No	No									
Schedule 1	0.68	0.97		No									
Schedule 1 (× 5)	0.75	1.07	1.11										
Schedule 1						No	Yes						
Schedule 1 Minus load 1					0.94		Yes						
Schedule 1 Minus load 8					1.14	1.22							
Schedule 1 (8 step)									Yes				
Schedule 1 (4 step)								1.23					
Schedule 1											No	Yes	Yes
Schedule 2										1.07		Yes	Yes
Schedule 3										1.83	1.61		No
Schedule 4										1.55	1.44	0.90	

	Yes
0.70	

Yes — Sample $\sum \frac{n}{N}$ geometric means are significantly different

0.70 — Ratio of sample $\sum \frac{n}{N}$ geometric means, $\frac{\text{Top group}}{\text{Side group}}$

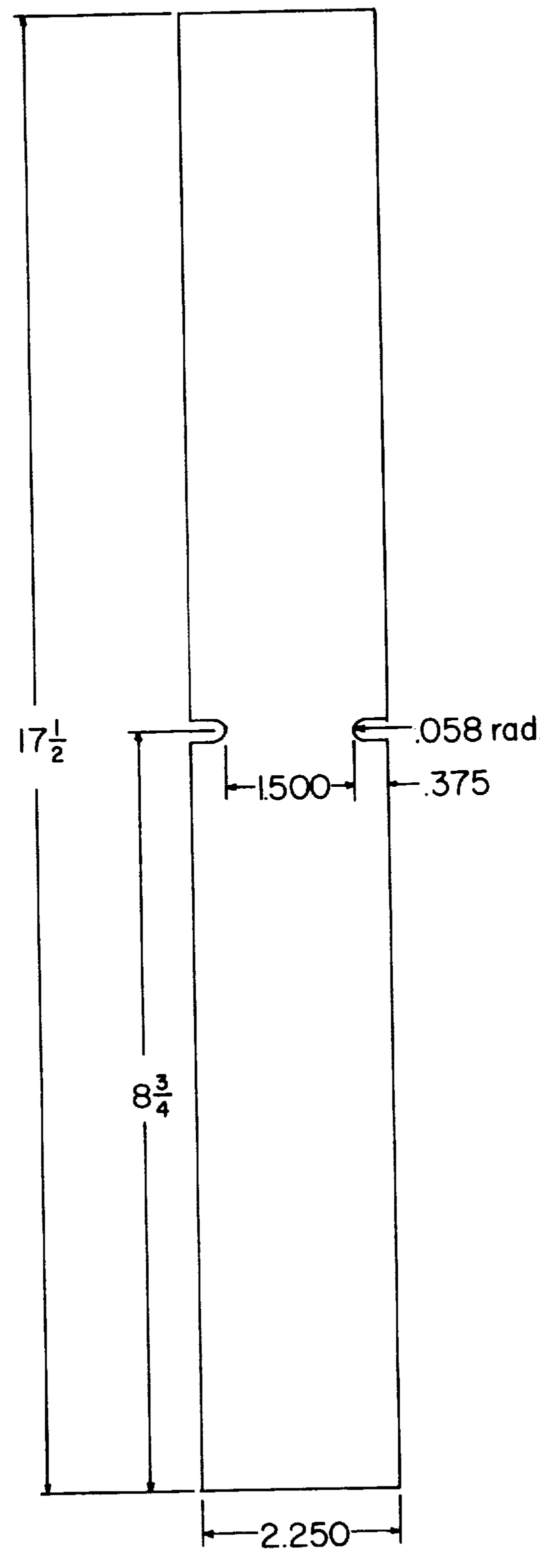

Figure 1.- Sheet-specimen details. All dimensions are in inches.

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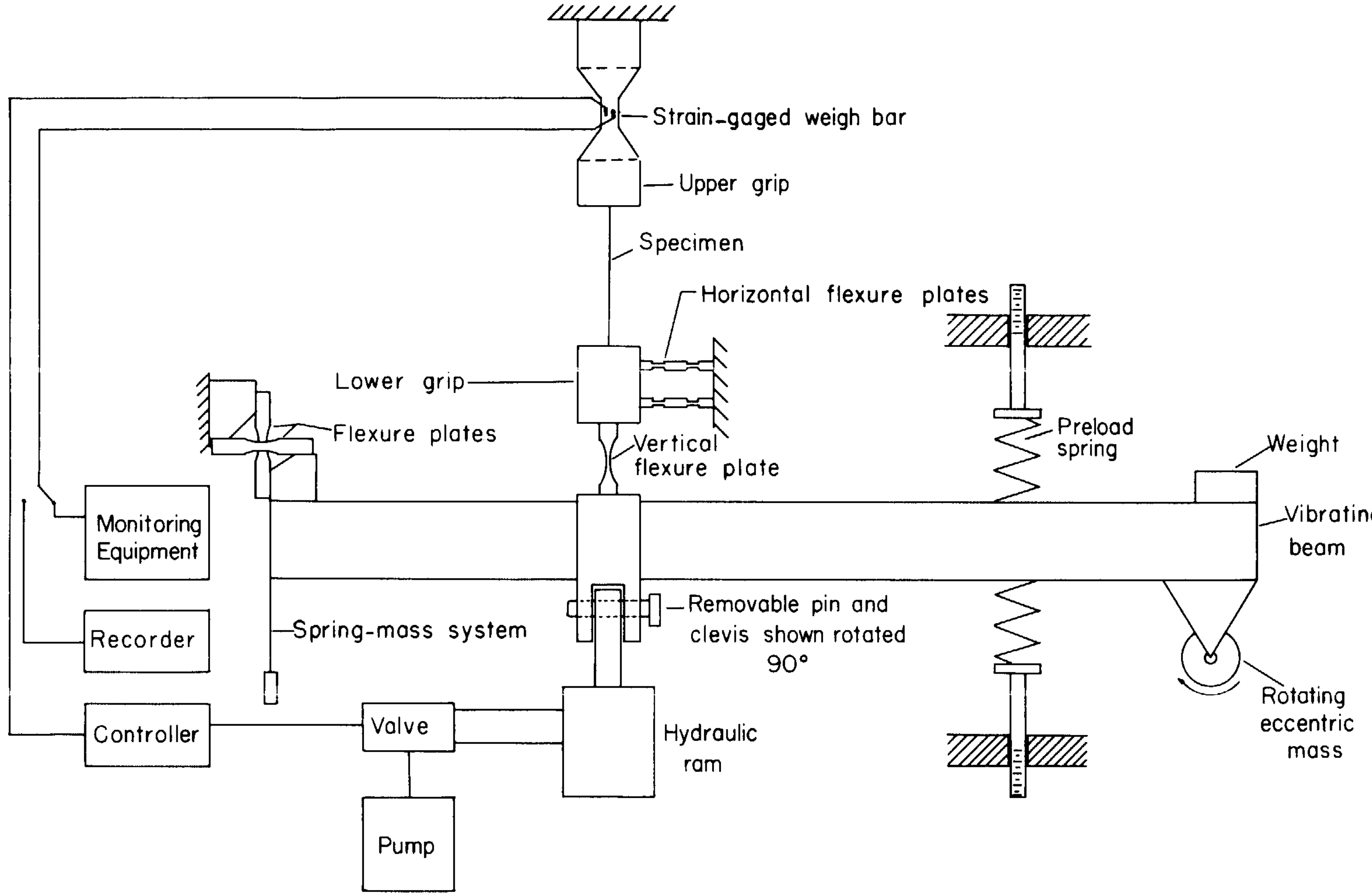

Figure 2.- Schematic diagram of fatigue testing machine.

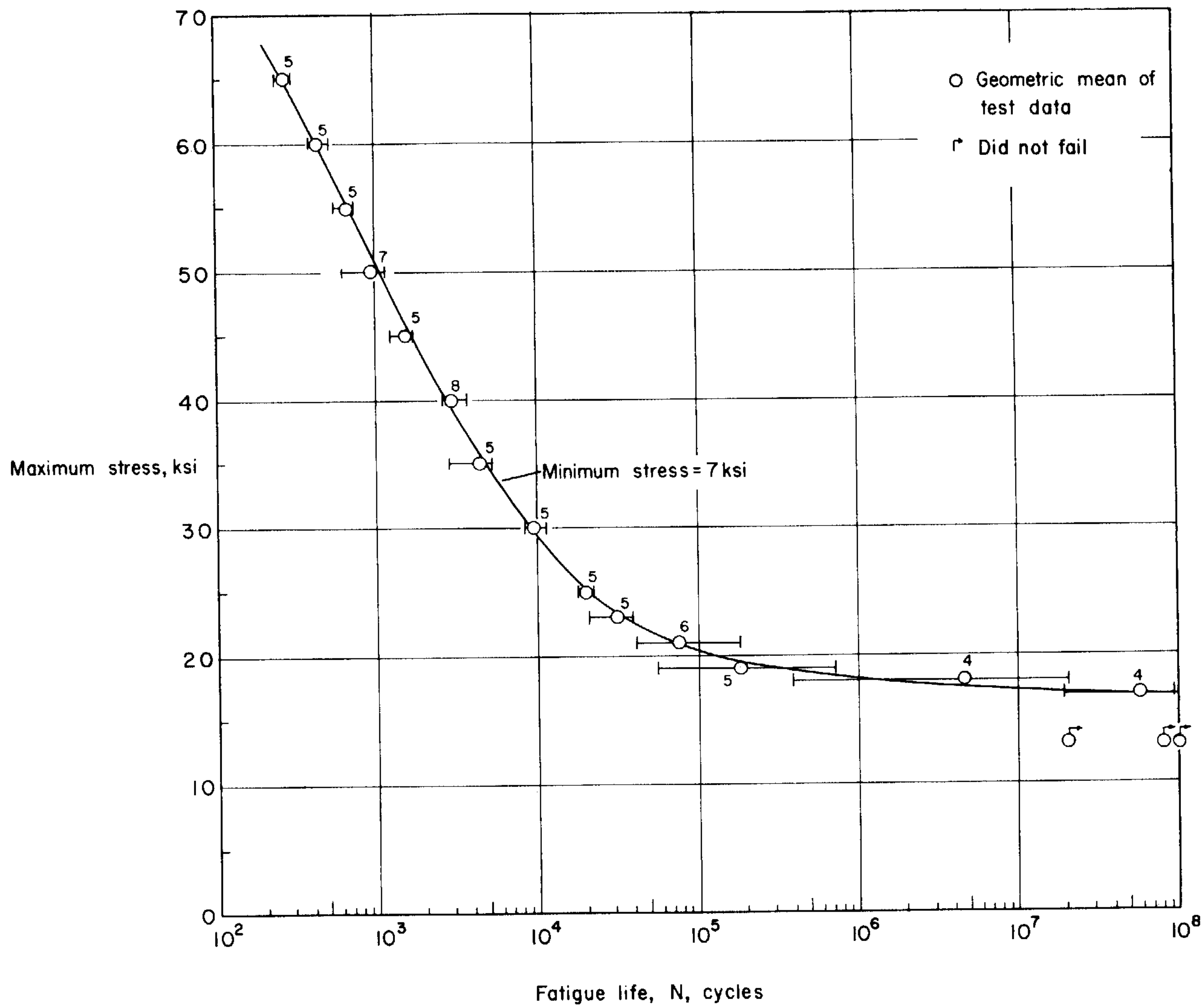

Figure 3.- Results of constant-amplitude fatigue tests of 7075-T6 aluminum-alloy specimens. (Ticks represent scatter bands and numerals indicate number of tests in each group.)

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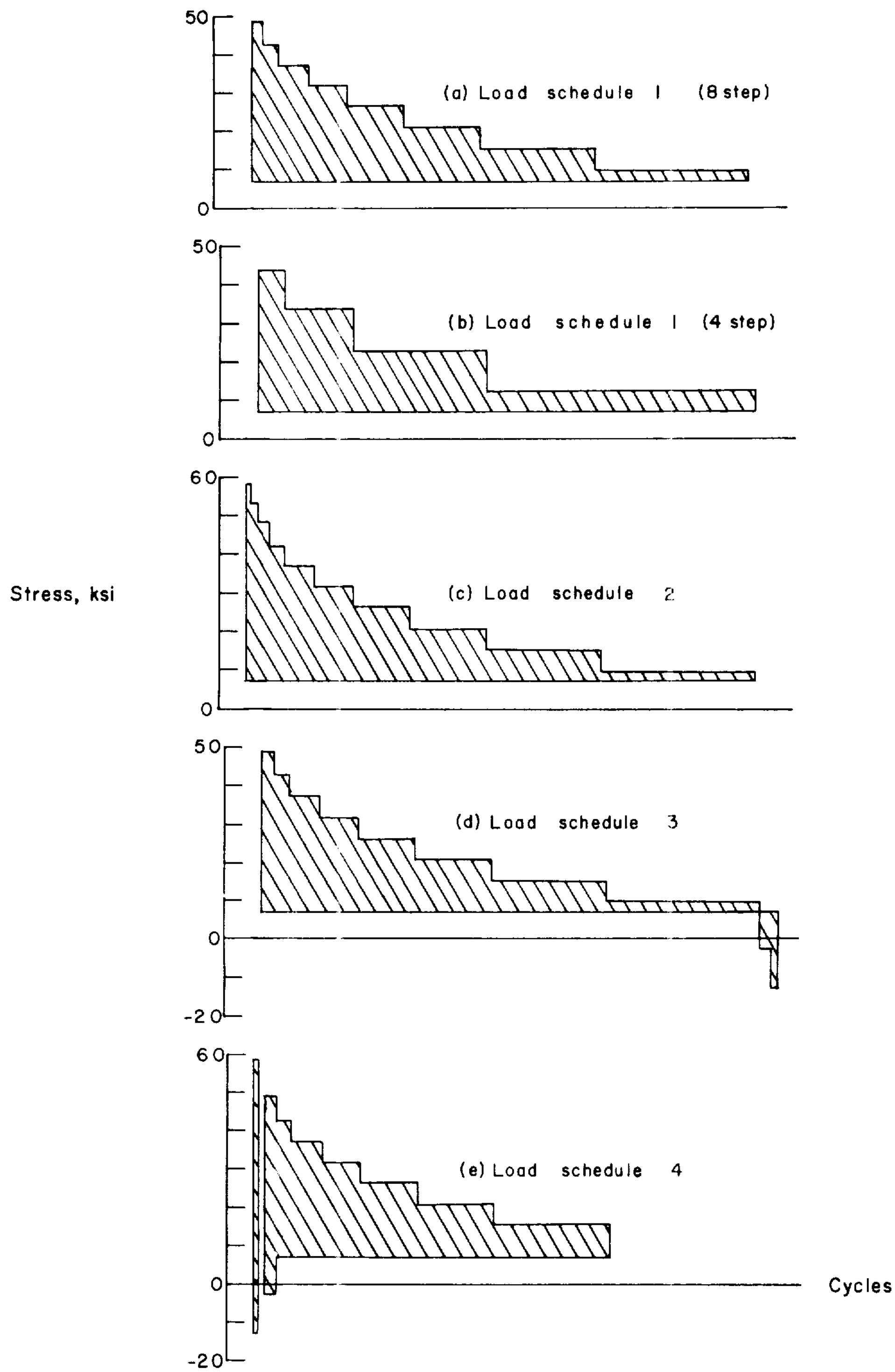

Figure 4.- Schematic diagrams of loading schedules.

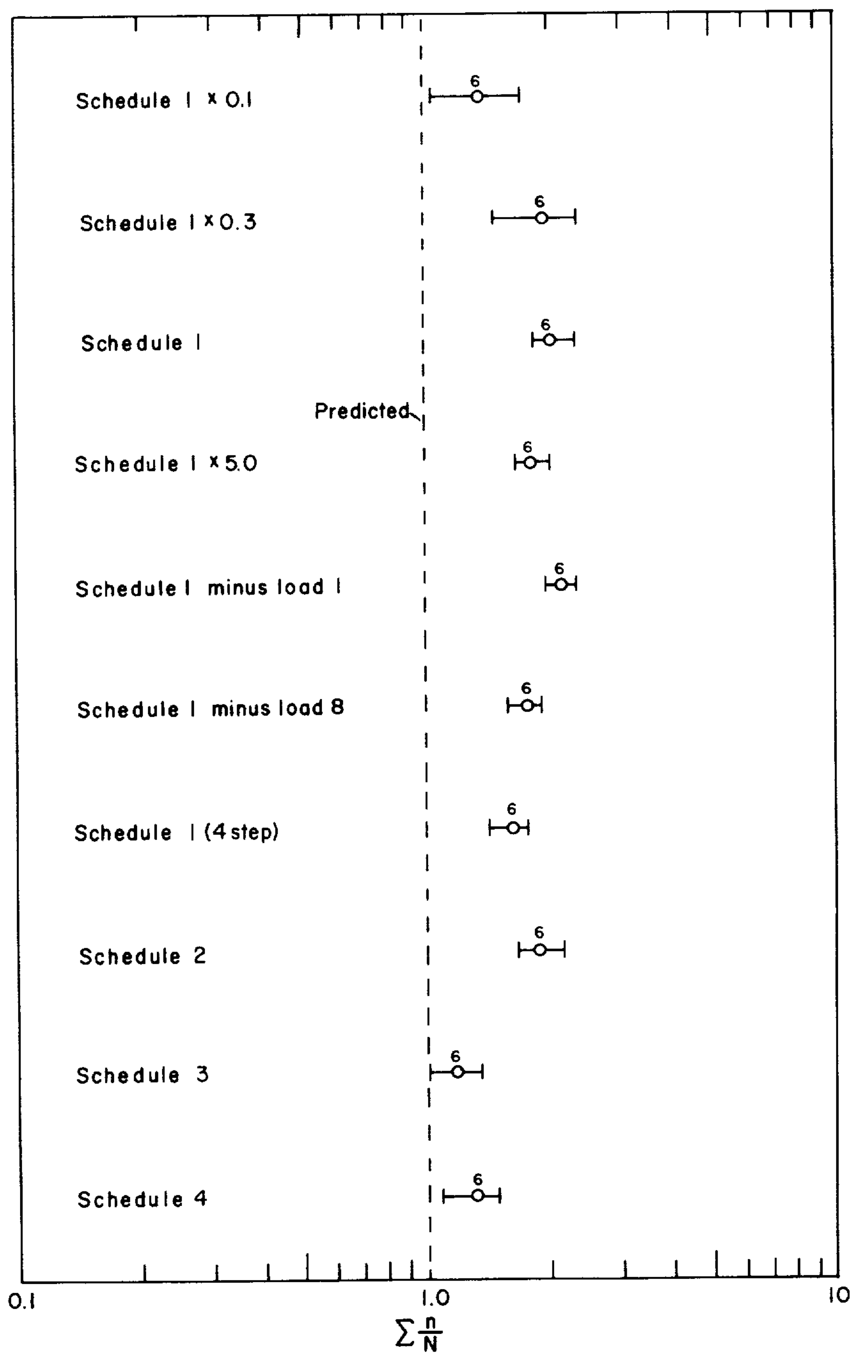

Figure 5.- Schematic presentation of results of variable-amplitude fatigue tests of 7075-T6 aluminum-alloy specimens. (Ticks represent scatter bands and numerals indicate number of tests in each group.)

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